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Mc GRAW-EDISON COMPANY
GROUNDWATER MODELING
OF
AQUIFER RESTORATION
FOR
ALBION, MICHIGAN PLANT SITE

December 1984

Project No. 84863/215-6, 22

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BACKGROUND

This report has been prepared to detail the purpose, methodology and results of the numerical transport model developed by Drs. Pinder and Babu. The limits of capture and containment of the plume using various remedial pumping rates as predicted by the model are presented. The influence on the groundwater level that may result from remedial pumping is shown for pumping rates of 2000 gpm and 3000 gpm. A discussion of the influence of several wells instead of a single well is included.

Hydrogeological investigations of groundwater flow phenomenon are difficult because of the many variables encountered in a dynamic 3-dimensional flow regime. Chemical transport processes and associated dispersion phenomenon result in substantially more complexity. The geology in the vicinity of the McGraw-Edison site consists of glacial spillway sediments and till deposits overlying the Marshall sandstone formation. The wide range of permeability in the glacial material results in a strong 3-dimensional flow character in the aquifers. A satisfactory evaluation of this complex hydrogeology can only be achieved by use of a 3-dimensional numerical transport model.

COMPUTER MODEL

Introduction

Computer models are formulated to simulate the physical behavior of complex groundwater systems. Advection and dispersion processes are simulated to indicate trends in chemical transport and to provide an aid in understanding and interpreting the physical situation. The model output can be utilized to test the reasonableness of basic hypotheses concerning the dynamics of the system that have been formulated a prior from field data. Models can be utilized as a predictive tool to estimate future conditions and trends. The certainty of the prediction depends, among other things, on the extent of the investigation into the physical system and the accuracy of the input parameters.

Development of a computer model initially requires an understanding of the groundwater system. An evaluation and interpretation of available field data result in the formulation of a conceptual model of the flow system. Missing data that are needed to clearly define the hydrogeological systems must then be generated. The extent of the area to be modeled, boundary conditions and somewhat idealized aquifer geometry are determined.

The physical data is then translated into mathematical terms. Numerical analysis allows the simultaneous solution of the partial differential equations that describe the hydraulic head and chemical concentration distribution at a specified time.

The accuracy of the model simulations are verified by a comparison of the calculated values with observed data. A trial and error procedure is utilized in which initial conditions and input parameters are adjusted within a reasonable range until the model satisfactorily generates known behavior.

A final step in the development of the model is an analysis of the sensitivity of the output to the assumed input parameters. Parameter values are each varied over a range of uncertainty to isolate the effect each parameter has on the simulations and to assess the relative importance of the various parameters.

Development

An extensive hydrogeological investigation was completed prior to the development of the model by Drs. Pinder and Babu. Beginning in the fall of 1980, Testing Services Corporation of Wheaton, Illinois (TSC) began the construction of soil borings, monitoring wells and lysimeters at the plant site. Groundwater samples were periodically collected from the monitoring wells and local domestic wells. During construction of the monitoring wells, soil samples representative of the materials at the site were collected. Variable head permeability tests were performed on 22 soil samples and 2 sandstone core samples to estimate hydraulic conductivity. Atterburg limit and grain size distribution tests were also performed on selected soil samples collected from the borings. A standard penetration test blow count was taken

during completion of the soil borings at each change in the lithology. Complete descriptive drilling logs were recorded for each boring. Groundwater samples collected by TSC from monitoring wells, domestic wells and lysimeters were analyzed for concentrations of TCE. The results of the investigation by TSC was presented in a report entitled, "HYDROGEOLOGIC STUDY, MCGRAW-EDISON FACILITY, ALBION, MICHIGAN".

Drs. Pinder and Babu began their hydrogeological investigation of the Albion plant site in the spring of 1982. Drs. Pinder and Babu directed the activities of TSC during the remainder of 1982. The data obtained by TSC was evaluated and interpreted to acquire an understanding of the characteristics of the hydrogeology at the site. Additional monitor wells were installed as required to provide a complete understanding of the nature of the aquifer system. A fence diagram was prepared using available drilling logs from borings at the site to provide a 3-dimensional view of the lithology.

Static water levels observed in monitor wells at the site were evaluated to obtain an understanding of the groundwater flow processes at the site. This data was evaluated by a procedure that allowed the determination of flow velocity in three dimensions (L. M. Abriola and G. F. Pinder, 1982). This analysis indicated a strong 3-dimensional flow character in the aquifer system. The existence of two flow directions was indicated from the evaluation: a southerly flow at wells constructed in the upper portion of the aquifer and a westerly flow in the lower aquifer.

The results of analyses of groundwater samples were reviewed to determine the probable concentration of contamination in the groundwater. This review also was used to estimate possible locations for sources of TCE. A graphical presentation of TCE concentration over time at each monitor well was prepared to indicate trends in the strength and the locations of TCE in the groundwater.

A pumping test of the existing fire well was completed in June 1982 by Dan Raviv Associates, Inc., under the direction of Drs. Pinder and Babu. The pumping test consisted of two parts. The first part involved injecting water pumped from the supply well into the fire well for 24 hours. Water levels

were measured in the pumping and recharge wells and 14 observation wells during the recovery period. During the second test, the fire well was pumped at a continuous rate of 2000 gpm for 48 hours, with the effluent discharged into the storm sewer. Water levels were measured in the pumping well and 19 observation wells for the duration of pumping and for a 24-hour recovery period. The purpose of the test was to obtain information on the specific yield and capacity of the fire well, evaluate the characteristics of the aquifer and to induce changes in the groundwater level that could be used to help calibrate the model. The time vs drawdown data were analyzed using the Theis nonequilibrium formula for leaky confined aquifers, the Theis recovery method and Jacob's method for solution of nonequilibrium equations. This analysis was used to estimate the aquifer transmissivity and storage coefficient.

The hydrogeological investigation by Drs. Pinder and Babu allowed them to formulate a conceptual model of the flow system in the vicinity of the plant site. This information was then input into a 3-dimensional numerical transport model. The numerical model calculated the spatial distribution of hydraulic head and TCE concentrations at specific times by use of a combination of the finite element and finite difference methods for solution of partial differential equations. The Galerkin finite element technique was applied in the horizontal plane. The finite element method allows a flexible discretization of the system. Therefore, the shape of the elements in the grid can be adjusted to allow smaller elements and better accuracy in the immediate vicinity of the plant site. The finite difference method was applied to the vertical cross-section.

Figure 1 presents the horizontal cross-section of the grid. The finite element grid, consisting of 556 elements and 588 nodes (joints at which lines intersect are nodes), was placed in three layers on the system. The element size in the dense central region is approximately 132 feet. A constant head boundary was imposed in the upper layer, and on the north, east and west sides of the lower layer. A no-flow boundary was imposed for the south side of the lower layer boundary (Kalamazoo River). The hydraulic heads at the boundary of the middle layer were determined where appropriate by linear interpolation from the upper and lower layers.

An idealized flow system consisting of both an upper and lower aquifer with an intervening aquitard was then assumed for the model. The upper aquifer was assumed to be a water table aquifer with an average thickness of approximately 10 feet. The upper aquifer is represented by the upper grid layer in the numerical model. An aquitard of varying thicknesses was input underlying the upper aquifer. The middle layer in the grid represents the aquitard. The lower confined aquifer with an assumed thickness of 400 feet is represented by the lower grid layer. The lower aquifer includes both permeable unconsolidated glacial deposits and the Marshall sandstone formation. An anisotropic flow system was imposed by setting the vertical conductivity equal to 10% of the horizontal conductivity. A horizontal hydraulic conductivity for the aquifers of 90 to 100 ft/day was determined from the results of the fire well pumping test and permeability tests of soil and rock core samples. The aquitard horizontal conductivity was set at 10^{-5} times the aquifer horizontal conductivity.

A review of drilling logs and water levels in the monitor wells at the site indicated the existence of permeable zones in the aquitard. The horizontal conductivity of the middle layer at these "windows" was set equal to the conductivity of the aquifer in the upper and lower layers. Direct flow of groundwater from the upper aquifer to the lower aquifer was assumed in the location of the windows due to a hydraulic gradient downward between the aquifer throughout the site. The location of the windows in the grid are indicated on Figure 1.

Calibration

Accuracy in the reproduction of the physical behavior observed in the groundwater flow system by the model was achieved by a calibration of input parameters and initial conditions. Calibration of the model was completed in two stages. The first step involved obtaining an acceptable accuracy in the simulation of the groundwater flow. Secondly, the chemical transport parameters were adjusted as required to achieve a satisfactory reproduction of the observed TCE plume development.

Calibration of the model for flow analysis was completed by a trial and error process in which parameters were adjusted until an acceptable reproduction of both steady state and dynamic advection processes was achieved. The steady state flow conditions were modeled assuming an aquifer flow system influenced by local pumping of 320 gpm at the Brook's Foundry wells only. This corresponds with the period from July 8, 1981 to June 28, 1982 during which time the Clark Street municipal well field and the McGraw-Edison supply well were not in operation. Water levels in the monitor wells at the plant site had been measured frequently during this period. A comparison of the computer-simulated piezometric surface with water level readings from the monitor wells is shown in Figure 2 and 3 for the lower and upper aquifers, respectively.

Calibration of the model for analysis of dynamic flow conditions was completed by a simulation of the fire well pumping test. Flow rates of 224 gpm at the Clark Street well field, 320 gpm at the Brook's Foundry wells, and 2000 gpm at the fire well were input into the model. The computer-simulated piezometric surface map is compared to water levels measured in the observation wells for the time of 16 hours following initiation of the pump test in Figures 4 and 5 for the lower and upper aquifers, respectively.

The good correlation between observed and calculated spatial head distribution in Figures 2 - 5 indicates that the model has been calibrated sufficiently to analyze both steady state and dynamic groundwater flow conditions.

Calibration of the model for analysis of chemical transport was completed by a trial and error adjustment of the initial input conditions and relevant parameters. TCE source locations and concentrations were important initial input conditions for chemical transport. The location and size of the windows were also important input conditions due to the existence of a downward hydraulic gradient between the upper and lower aquifers throughout the site. Dispersion coefficients determine the extent to which TCE deviates both laterally and longitudinally from the average lineal velocity vector.

A final step in the calibration process was the simulation of the dynamics of the hypothetical TCE plume for the period from 1949 to 1983. Variable flow rates were set at the Clark Street well field while a constant pumping rate of

320 gpm was assumed for the Brook's Foundry wells. The McGraw-Edison supply well was assumed to pump at a constant rate of 500 gpm from 1949 to 1979, at which time it was taken out of operation. The TCE plume evolution was simulated for 1949 to 1983 with a constant concentration of 100 - 35,000 ppb at the east side of the site. A satisfactory comparison of the computed extent of TCE to the observed extent was shown in the simulations. Therefore, the model can be utilized as both an analytical and a predictive tool of chemical transport patterns and trends.

DISCUSSION OF MODEL SIMULATIONS

Evolution of the Plume of Contamination.

Figures 6 and 7 depict the computed extent of the TCE plume in the lower and upper aquifers in 1983. Note that in comparing the computed and observed concentrations in Figure 7, the apparent discrepancy to the south of the plant is due to the definition of what constitutes an upper aquifer. In computing concentrations, Pinder and Babu (1984) recognized that there is no confining bed to the south and consequently attributed the contaminant in this single-aquifer region to both aquifers. The observed data (contouring) in Figure 7 however, is based upon an alternative definition based upon well depth criteria. When Figures 6 and 7 are taken together in this context, it is found that the computed plume geometry in this area matches the observed configuration very well.

The apparent discrepancy to the west of the plant in Figure 7 for the computed and observed concentrations appears to be due to a possible secondary source of contamination that was not included as a source in the model. However, the dynamics of the system shown by the computed plume geometry match the observed data very well.

Remedial Pumping

Model simulations predicting the retraction of the TCE plume in the lower and upper aquifers are depicted in Figures 8 and 9, respectively. These figures show the extent of TCE in each aquifer after a pumping period of 5 years. In

addition, the extent of TCE after pumping 6 months in the lower aquifer and after pumping one year in the upper aquifer are also shown in these figures to indicate the relative rate of retraction of the TCE plume due to the remedial pumping. A remedial pumping rate of 3000 gpm at the existing fire well and 100 gpm from eight wells in the upper aquifer was assumed for these simulations. Total containment and retraction of the TCE plume is shown for both aquifers. A rapid rate of retraction of the TCE is followed by a more gradual rate. This appears to be due to the conservative assumption of continued input of a constant source of TCE at the east end of the site.

The extent of groundwater capture in the lower aquifer is shown on Figure 10, in which computer-generated steady-state piezometric contours (during remedial pumping) are shown. The area within the total capture zone extends far beyond the TCE plume. The approximate hydraulic boundaries between the fire well, the Clark Street wells and the Brook's Foundry wells are also depicted. These boundaries were determined for this report by a flow net analysis using the computer-generated piezometric surface.

The hydraulic boundary between the Clark Street municipal well field and the fire well is shown to be beyond the TCE plume. The hydraulic boundary at Brook's Foundry is shown at the edge of the TCE plume. However, the vast majority of the water supply is provided from upgradient (east) of the foundry.

The approximate extent of groundwater capture in the upper aquifer is illustrated in Figure 11. It is observed that where a distinct upper aquifer exists, a major portion of the plume is captured. To the south, where one aquifer is believed to exist, the remaining segment of the plume is captured via lower aquifer pumping.

Alternate Remedial Pumping Rates

A remedial pumping rate of 2000 gpm at the fire well was also simulated by the model. It was determined that significant restoration of both the lower and upper aquifers was possible over the five-year pumping period, but that a substantial residual contaminant concentration remained in the lower aquifer. Thus, this strategy is deemed unsatisfactory.

Influence On Groundwater Levels

The computed influence of total remedial pumping on water levels in the neighborhood of the site is given in Figures 12 - 15. Figures 12 and 13 indicate the computed drawdown (in feet) to be anticipated in the upper and lower aquifers, respectively, when the remedial pumping in the lower aquifer is 3000 gpm. Figures 14 and 15 show the computed drawdowns (in feet) in the upper and lower aquifers, respectively, when the remedial pumping rate in the lower aquifer is 2000 gpm.

These estimates are conservative. The drawdowns are computed for the following pumping changes. For Figures 12 and 13, Clark Street city well - 1000 gpm, Brooks Foundry - 320 gpm, changed to city well - 1200 gpm, fire well - 3000 gpm, and Brooks Foundry - 320 gpm. For Figures 14 and 15, city well - 1000 gpm, Brooks Foundry - 320 gpm, changed to city - 1200, fire well - 2000 gpm, and Brooks Foundry - 320 gpm. In both cases, purge wells in the upper aquifer pump at a total of 48 gpm.

The influence on the groundwater resulting from remedial pumping at an equal total rate will not vary significantly by pumping from numerous wells instead of pumping from only one well. A locally higher or lower drawdown may result in the immediate vicinity of the pumping wells. However, for distances beyond the immediate vicinity of the pumping wells, minor differences in distances from the pumping influences will have essentially no impact on the total observed drawdown.

CONCLUSION

The 3-dimensional numerical transport model of the flow system at McGraw-Edison, developed by Drs. Pinder and Babu, was developed in accordance with procedures outlined in current literature on groundwater modeling (Gillham and Cherry, 1982; McLaughlin, 1984; Hamilton, 1982; Anderson, 1984, et al). A familiarity with the physical characteristics and behavior of the flow system were utilized to calibrate the model for flow and chemical transport analysis. Simulation of known conditions was achieved to assure that the model could be utilized as a suitable evaluative tool.

The results of the model indicate that containment and retraction of the plume should occur at a pumping rate of 3000 gpm, but that 2000 gpm was unacceptable.

The influence of the proposed remedial pumping schemes on groundwater levels in the lower aquifer does not appear to be significant for offsite wells located in the Marshall sandstone. A drawdown of less than 5 feet should not adversely affect a properly constructed well. A reduction in the flow rate for very low head artesian springs is possible within an area of approximately 1.5 miles of the site. The use of one pumping well as opposed to wells in close proximity would result in very similar effects on the groundwater drawdown at points beyond the immediate vicinity of the well(s).

The hydrogeology in the vicinity of McGraw-Edison consists of a complex flow system with a strong 3-dimensional character and different horizontal flow directions at various depths in the system. Evaluation of groundwater flow and chemical transport processes is only possible by use of a 3-dimensional numerical modeling procedure. A model can be utilized as a useful qualitative tool to predict trends in the physical behavior.

Problems in using a model normally are the result of interpreting the data. However, though the model cannot be used to accurately define a 1.5 ppb isoconcentration contour, it can produce a helpful plot of a 200 ppb isoconcentration line. In order to close the gap between what is technically feasible and the objective to contain and retract TCE concentrations \geq 1.5 ppb, remedial alternatives are evaluated with a conservative use of the model. This approach is felt to demonstrate that the objective of the Consent Decree will be met.

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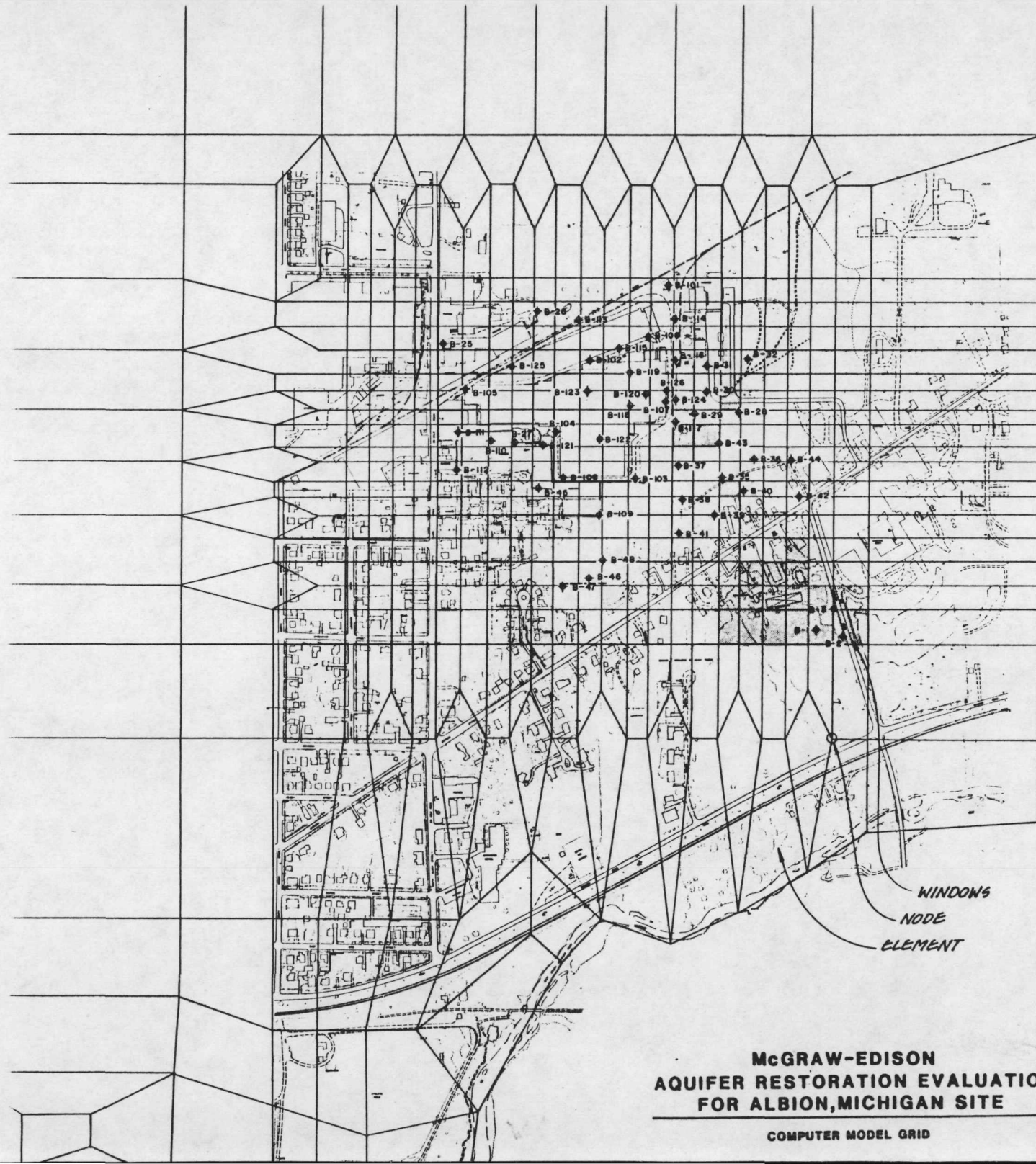
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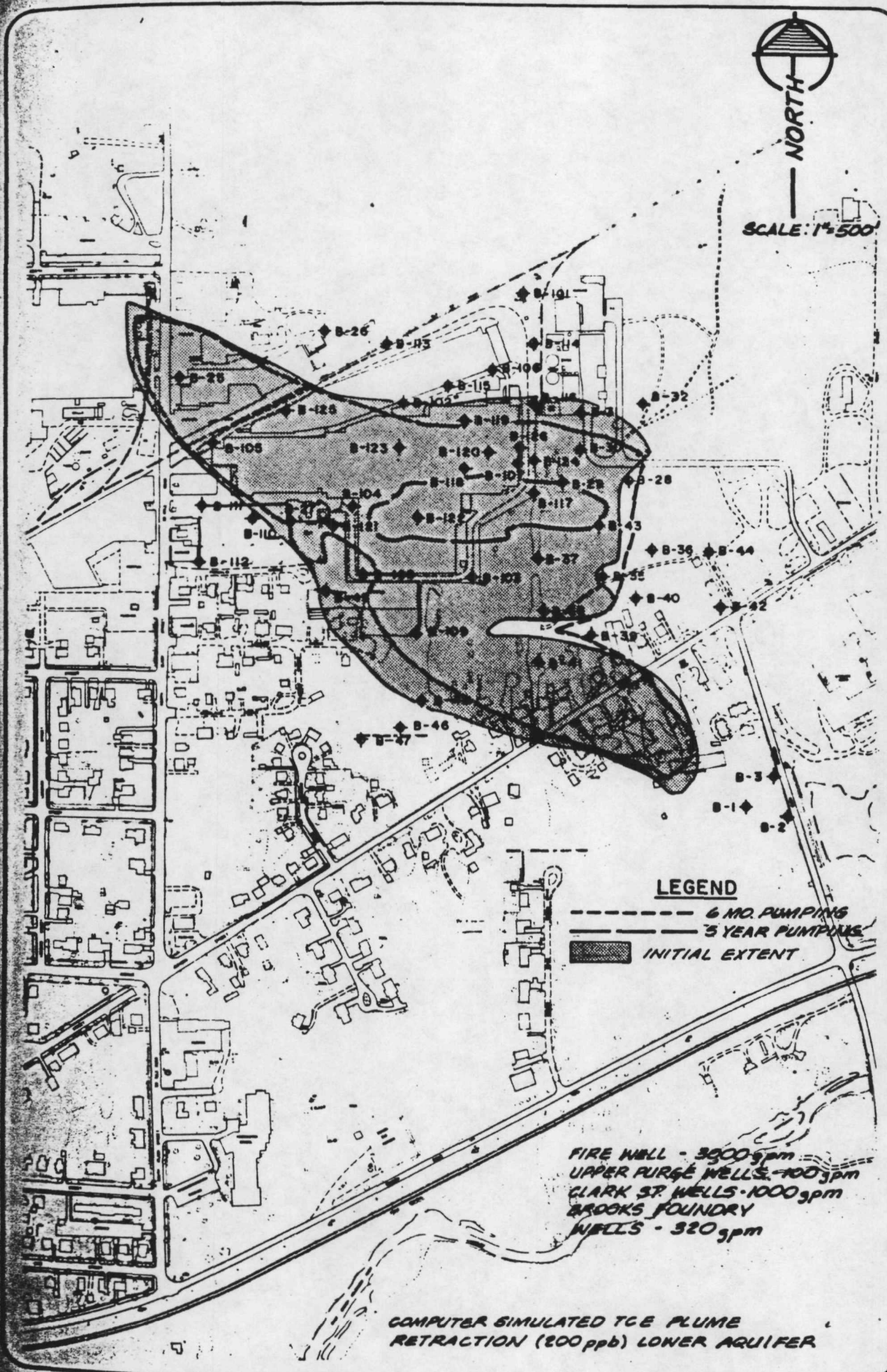
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**McGRAW-EDISON
AQUIFER RESTORATION EVALUATION
FOR ALBION, MICHIGAN SITE**

COMPUTER MODEL GRID



NORTH
SCALE: 1"=500'

DATE	BY	DATE	BY	DATE	BY

FISHBECK-THOMPSON
CARR & HUBER, INC.
 CONSULTING ENGINEERS
 1800 EAST BERTLUM ST.
 GRAND RAPIDS, MICHIGAN 49503
 616 961-1111

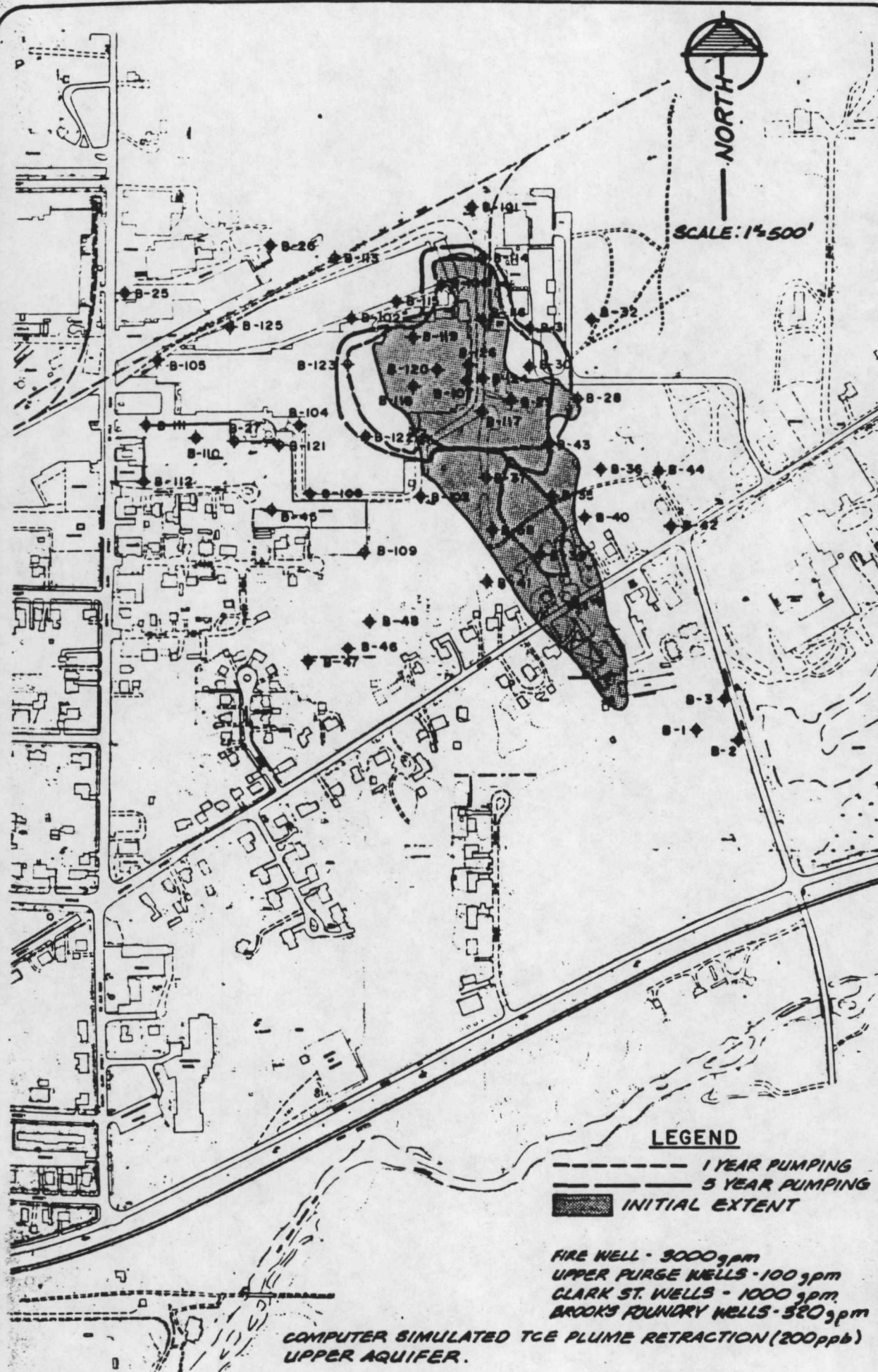
McGRAW - EDISON COMPANY
 ALBION, MICHIGAN
 GROUNDWATER MODELING OF
 AQUIFER RESTORATION

PROJECT NO.
84863
 FIGURE NO.
8

LEGEND
 --- 6 MO. PUMPING
 — 3 YEAR PUMPING
 ■ INITIAL EXTENT

FIRE WELL - 3000 gpm
 UPPER PURGE WELLS - 100 gpm
 CLARK ST. WELLS - 1000 gpm
 BROOKS FOUNDRY
 WELLS - 320 gpm

COMPUTER SIMULATED TCE PLUME
 RETRACTION (200 ppb) LOWER AQUIFER



SCALE: 1"=500'

REVISED	BY	DATE	REASON

FISHBECK-THOMPSON
CARR & HUBER, INC.
 CONSULTING ENGINEERS

FOR EAST BRANCH OF
 GRAND RIVER, MICHIGAN

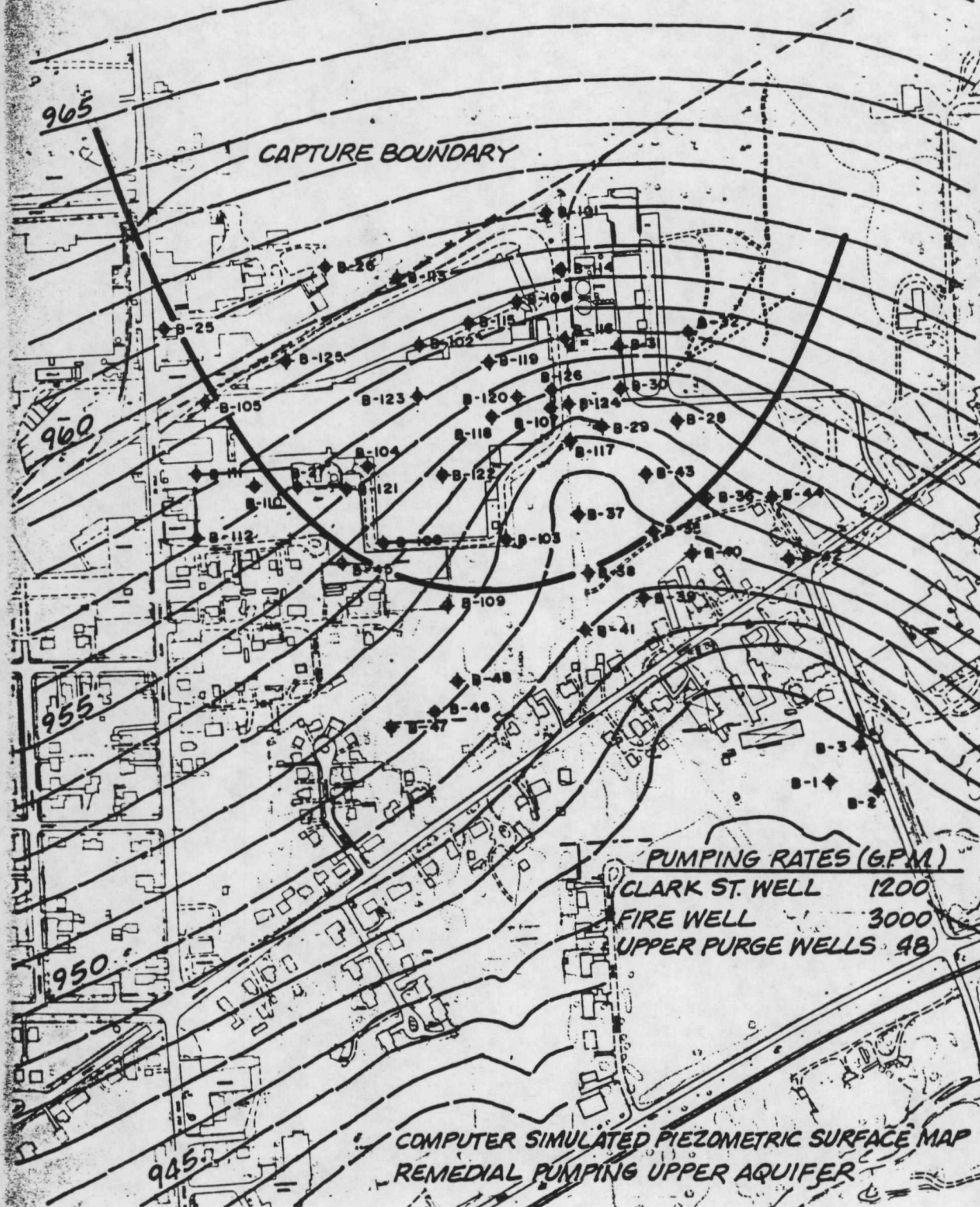
McGraw - Edison Company
 ALBION, MICHIGAN
 GROUNDWATER MODELING OF
 AQUIFER RESTORATION

PROJECT NO.
 84863
 FIGURE NO.

9



SCALE: 1"=1000'



COMPUTER SIMULATED PIEZOMETRIC SURFACE MAP
REMEDIAL PUMPING UPPER AQUIFER

FISHBECK-THOMPSON
CARR & HUBER, INC.
CONSULTING ENGINEERS
1001 EAST WILLOW & E
LAURENCE, MICHIGAN

MCGRAW - EDISON COMPANY
ALBION, MICHIGAN
GROUNDWATER MODELING OF
AQUIFER RESTORATION

PROJECT NO.
84863
FIGURE NO.

11

REVISIONS	DATE	BY	CHKD	DATE	BY	CHKD
1	12-85	J.E.S.		12-7-84		
2						
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6						
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1000 G.P.M. CAPTURE BOUNDARY

CLARK ST. WELL

BROOKS WELL

320 G.P.M. CAPTURE

McGRAW-EDISON AQUIFER RESTORATION EVALUATI FOR ALBION, MICHIGAN SITE

COMPUTER SIMULATED
PIEZOMETRIC SURFACE MAP
DURING REMEDIAL PUMPING
LOWER AQUIFER

FIRE WELL: 3000gpm
UPPER PURGE WELLS: 100gpm
CLARK ST. WELLS: 1000gpm

LEGEND

OBSERVED T.E. EXTENT

